

# Evolution of massive stars at very low metallicity including rotation and binary interactions

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**Abstract.** We discuss recent models on the evolution of massive stars at very low metallicity including the effects of rotation, magnetic fields and binarity. Very metal poor stars lose very little mass and angular momentum during the main sequence evolution, and rotation plays a dominant role in their evolution. In rapidly rotating massive stars, the rotationally induced mixing time scale can be even shorter than the nuclear time scale throughout the main sequence. The consequent quasi-chemically homogeneous evolution greatly differs from the standard massive star evolution that leads to formation of red giants with strong chemical stratification. Interesting outcomes of such a new mode of evolution include the formation of rapidly rotating massive Wolf-Rayet stars that emit large amounts of ionizing photons, the formation of a long gamma-ray bursts and a hypervolae, and the production of large amounts of primary nitrogen. We show that binary interactions can further enhance the effects of rotation, as mass accretion in a close binary spins up the secondary.

**Keywords:** Stars:evolution, Stars:rotation, Stars:binary

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## 1. INTRODUCTION

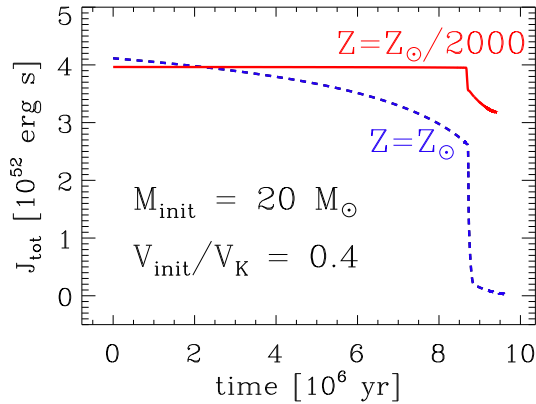
Massive stars affect the evolution of the early universe in a number of ways. They are believed to be the main source of reionizing photons at high redshift, and their explosions provide large amounts of energy into the surrounding medium. Most elements heavier than helium begin to exist in the early universe due to nucleosynthesis in massive stars. The history of star formation and the evolution of galaxies in the early universe are therefore closely related to such feedback from massive stars. This has motivated many theoretical studies on the evolution of massive stars of the first and second generations, which are characterized by zero/low metallicity.

Mass loss due to stellar winds from massive stars is mainly driven by metal lines (Castor, Abbott & Klein 1975; Pauldrach, Puls & Kudritzki R.P. 1986; Vink, de Koter & Lamers 2001). As a result, metal poor massive stars are expected to lose only a small amount of mass and angular momentum and to be kept rotating rapidly, during their life times (see Ekström and Meynet, however, in this volume). Rotation – one of the primary factors to determine the evolution of massive stars – may thus play an even more important role in the evolution of massive stars in the early universe, compared to the case of galactic metal-rich massive stars. For instance, the high ratio of nitrogen to carbon abundance observed in extremely metal poor stars may be related to chemical mixing due to rotationally induced instabilities in massive stars in the early universe (Chiappini et al. 2006). Stellar cores could also more easily retain a

large amount of angular momentum at lower metallicity, resulting in the abundant production of energetic supernovae and gamma-ray bursts (Yoon & Langer 2005; Woosley & Heger 2006; Yoon, Langer & Norman 2006).

Detailed numerical simulations of the evolution of massive stars including the effects of rotation involve many uncertain physical processes such as the transport of angular momentum and chemical species due to rotationally induced instabilities. Studies by Langer et al. (1999), Heger, Langer & Woosley (2000) and Hirschi, Meynet & Maeder (2004) indicate that their adopted angular momentum transport mechanisms (Eddington Sweet circulations, shear instability and baroclinic instability) are too inefficient to explain the observed spin rates of white dwarfs and young neutron stars: their models predict one or two orders of magnitude higher spin rates than the observed values. More recent models adopting the prescription by Spruit (2000) for the Tayler-Spruit dynamo in differentially rotating radiative layers are shown to be more consistent with observations in terms of the spin rates of stellar remnants (Heger, Woosley & Spruit 2005; Suijs et al. in prep.). The validity of the Tayler-Spruit dynamo has recently been challenged by several authors (Denissenkov, Pavel, & Pinsonneault 2007; Zahn, Brun & Mathis, S. 2007) but it seems clear that an efficient braking mechanism that is comparable to what Spruit suggests is needed to explain observations.

Here we present recent models of both single and binary massive stars at very low metallicity including the Tayler-Spruit dynamo as well as other effects of



**FIGURE 1.** Total angular momentum in  $20 M_{\odot}$  models as a function of evolutionary time. The solid line and the dashed lines give the results with  $Z = 10^{-5}$  and 0.02 respectively.

rotation such as rotationally induced chemical mixing, enhanced mass loss near the break-up velocity and tidal interactions. We suggest that rotation could lead to very different types of massive star evolution at very low metallicity, compared to the case of metal rich stars. Implications for supernovae and gamma-ray bursts, and massive star feedback in the early universe are briefly discussed.

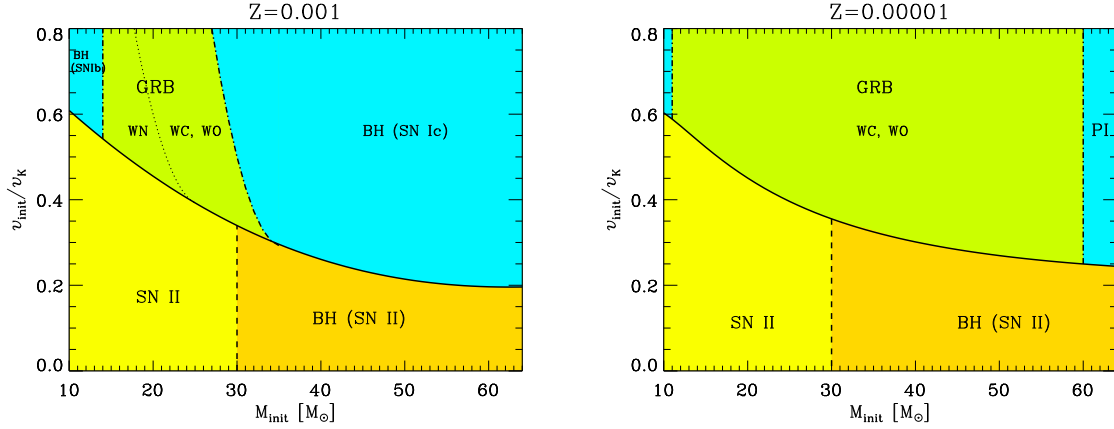
## 2. EVOLUTION OF SINGLE STARS AT VERY LOW METALLICITY

It is well known that many massive stars in our Galaxy as well as in the Small/Large Magellanic Cloud are rapid rotators (e.g. Maeder & Meynet 2000; Mokiem et al. 2006; Mokiem et al. 2007). One of the most important effects of rotation on the evolution of massive stars is rotationally induced mixing of chemical elements (Maeder & Meynet 2000; Heger & Langer 2000). In magnetic models, stars tend to rotate rigidly due to magnetic torques, and thus it is Eddington-Sweet circulations that mainly induce chemical mixing inside stars (Maeder & Meynet 2005; Heger, Woosley & Spruit 2005; Yoon & Langer 2005), rather than the shear instability that is important in non-magnetic models (Maeder & Meynet 2000; Heger, Langer & Woosley 2000; Meynet & Maeder 2002). Efficient chemical mixing across the boundary between the core and the envelope in a star by Eddington-Sweet circulations is usually prohibited due to the chemical gradient built up by nuclear burning in the convective core (Zahn 1992). If a star is born with a sufficiently large amount of angular momentum, however, mixing could occur on a shorter time scale than the nuclear burning time scale. I.e., the star becomes chemically homogeneous due to efficient

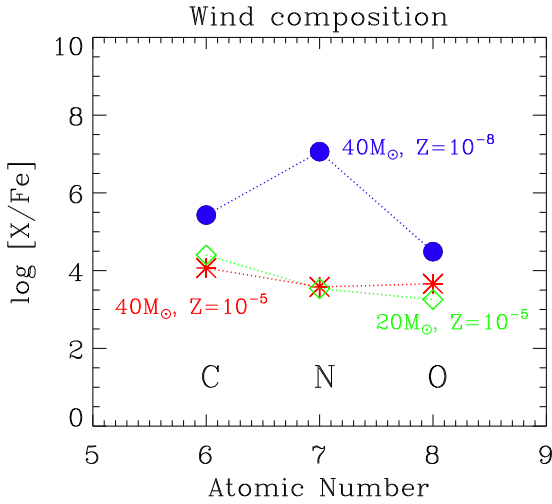
chemical mixing by Eddington Sweet circulations and the classical core-envelope structure is not developed (Maeder 1987; Langer 1992). Such a star would be gradually transformed into a rapidly rotating massive helium star (i.e., WR star) by the end of the core hydrogen burning. This mode of evolution is supposed to be particularly important for metal poor massive stars. At high metallicity, strong winds significantly spin down a massive star early on the main sequence, rendering rotationally induced mixing too inefficient to lead to the chemically homogeneous evolution (see Fig. 1).

In Fig. 2, we summarize how the evolution and final fate of massive stars differ according to the initial mass and rotational velocity, at two different metallicities, based on our stellar evolution models (Yoon, Langer & Norman 2006). Slowly rotating stars follow the classical evolutionary path such that they evolve redwards on the HR diagram, and end their life as a (super) giant with a thick hydrogen envelope. In this case, the core is strongly braked down during the giant phase by the heavy envelope, resulting in a specific angular momentum of the order of  $10^{14} \text{ cm}^2 \text{ s}^{-1}$  in the pre-collapsing core. Type II supernovae are the expected outcome, leaving millisecond pulsars or black holes as remnants depending on the initial mass.

On the other hand, the quasi-chemically homogeneous evolution of rapidly rotating stars have several interesting consequences. Avoiding the giant phase, some of them can retain a large amount of angular momentum in the core ( $j_{\text{CO}} \geq \sim 10^{16} \text{ cm}^2 \text{ s}^{-1}$ ) that may lead to production of a long gamma-ray burst (GRB) or a jet-induced energetic supernova/hypernova (Yoon & Langer 2005; Woosley & Heger 2006). A higher ratio of GRBs/HNe to SNe is predicted for lower metallicity (Yoon, Langer & Norman 2006), and the role of the GRBs/HNe feedback may be significant in the early universe. E.g., such energetic supernovae might have left unique nucleosynthetic signatures in the early universe as discussed by Nomoto (in this volume; Tominaga, Umeda & Nomoto 2007), and could have affected the history of star formation at high redshift (Kobayashi, Spiringel & White 2007). The very efficient rotationally induced chemical mixing also leads to abundant production of primary nitrogen as shown in Fig. 3. It is also remarkable that massive WR stars could be produced even at very low/zero metallicity due to the quasi-chemically homogeneous evolution, without the need of stellar winds. Such massive helium stars produce a few times more hydrogen ionizing photons and about 100 times more helium ionizing photons than the corresponding slowly rotating stars (Fig. 4). This might have consequences in the history of reionization in the early universe, depending on the initial rotational velocity function of the first and second generations of stars.



**FIGURE 2.** Final fate of our rotating massive star models at two different metallicities ( $Z = 0.001$  &  $0.00001$ ), in the plane of initial mass and initial fraction of the Keplerian value of the equatorial rotational velocity. To both sides of the GRB production region for  $Z = 0.001$ , black holes are expected to form inside WR stars, but the core spin is insufficient to allow GRB production. For  $Z = 0.00001$ , the pair-instability might occur to the right side of the GRB production region (see Heger et al 2003), although the rapid rotation may shift the pair instability region to larger masses. The dashed line in the region of non-homogeneous evolution separates Type II supernovae (SN II; left) and black hole (BH; right) formation, where the minimum mass for BH formation is simply assumed to be  $30 M_{\odot}$ . From Yoon, Langer & Norman (2006).



**FIGURE 3.** CNO elements yields by stellar winds from 3 different evolutionary sequences with  $M_{\text{init}} = 40$  and  $Z = 10^{-8}$  (filled circles),  $M_{\text{init}} = 40$  and  $Z = 10^{-5}$  (asterisks), and  $M_{\text{init}} = 20$  and  $Z = 10^{-5}$  (open squares).

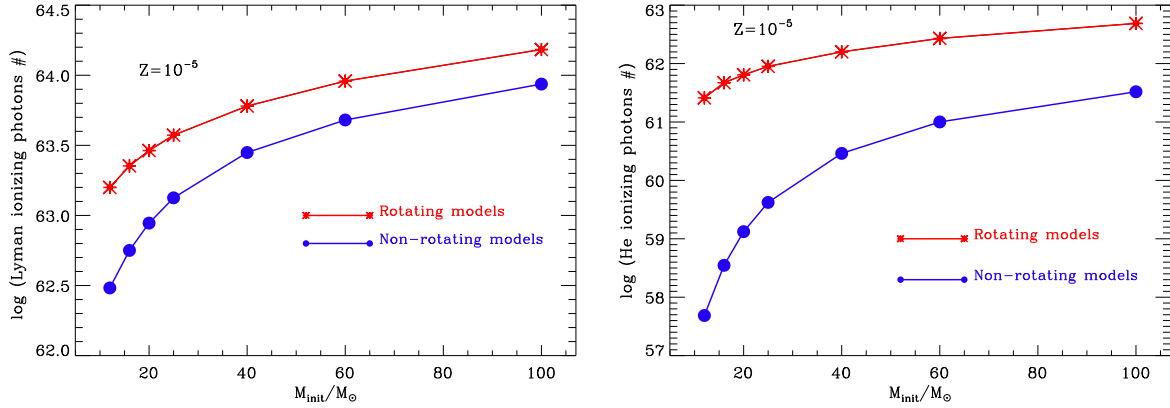
### 3. EVOLUTION OF BINARY STARS AT VERY LOW METALLICITY

Massive star evolution becomes much complicated by binary interactions (e.g. de Greve & de Loore 1992; Podsiadlowski, Joss & Hsu 1992; Pols 1995; Wellstein &

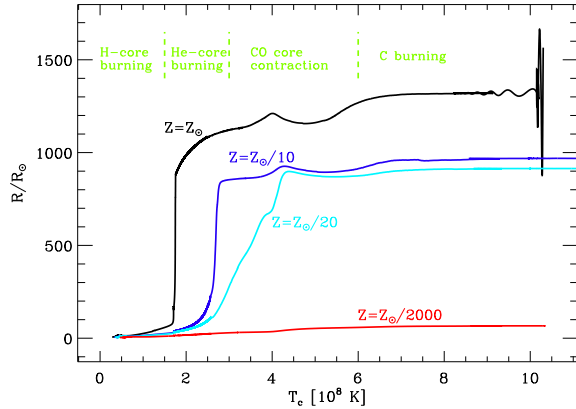
Langer 1999; Wellstein, Langer & Braun 2001). Binary star evolution is closely related to the change in the radii of the stellar components throughout the evolutionary stages. At solar metallicity, the envelope of a massive star drastically expands during the helium core contraction, and the case B mass transfer is most likely. As metallicity decreases, the rapid expansion of the envelope of a massive star is delayed to a later evolutionary stage as revealed in Fig. 5, and the Case C mass transfer would become more common (see de Mink et al. in this volume).

In the stellar models at very low metallicity ( $Z \leq 10^{-5}$ ), massive stars remain fairly compact with the maximum radius less than a few hundreds solar radii throughout the evolution if overshooting is ignored. This implies that a very close orbit may be required for a very metal poor star to undergo Roche-lobe overflows in a binary system. Our models also indicate that, at very low metallicity, mass transfer is usually dynamically stable regardless of the evolutionary stages of the primary, since the envelope remains radiative. However, rapid expansion of the envelope upto  $\sim 10^3 R_{\odot}$  during the CO core contraction is observed in the models with  $Z = 10^{-5}$  when overshooting is considered (de Mink et al. in this volume), and it remains uncertain whether very metal poor stars would become super-giants (see also Woosley in this volume).

A high mass transfer rate in a massive close binary usually leads to thermal expansion of the envelope of the mass-accreting star. This effect becomes, however, less significant for lower metallicity and binary systems can avoid contact or common envelope phase more easily (de



**FIGURE 4.** Total number of hydrogen (left panel) and helium (right panel) ionizing photons emitted throughout the evolution of massive star models at  $Z = 10^{-5}$ , as a function of the initial mass. The lines connecting asterisks and filled triangles give the results from rapidly rotating stellar models that undergo the quasi-chemically homogeneous evolution (see the text), and non rotating models, respectively.



**FIGURE 5.** Change in the radii of  $20 M_{\odot}$  models with  $V_{\text{rot,init}} = 0.3V_{\text{Kepler}}$  at four different metallicities, as a function of central temperature.

Mink et al., in this volume). Therefore, it is expected that formation of compact binary systems such as black hole X-ray binaries via common envelope phases should be less common at lower metallicity.

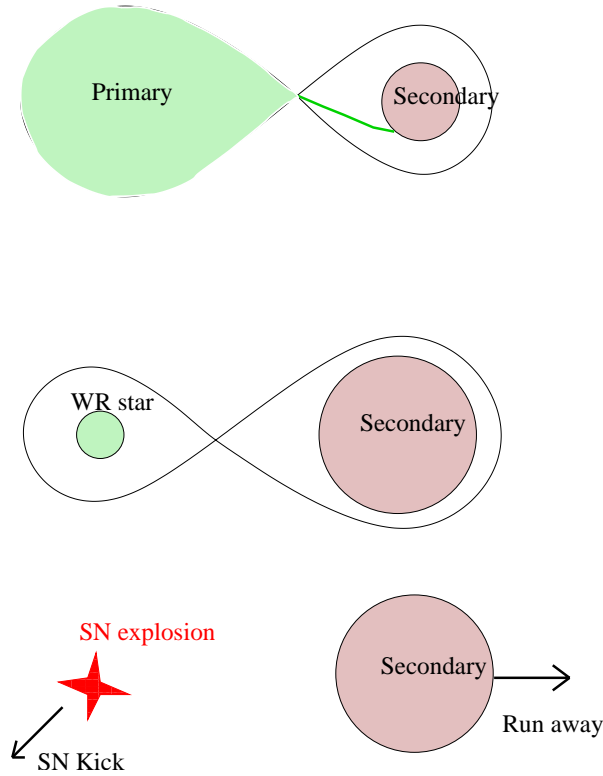
The role of rotation could be enhanced by binary interaction. A slowly rotating star could be spun up to the break-up velocity by mass accretion (Langer et al. 2003; Petrovic, Langer & van der Hucht 2005). Models with fast semi-convection show that rapid mass accretion leads to rejuvenation in mass-accreting stars, which weakens the chemical gradient between the core and the envelope (Braun & Langer 1995). All these effects of mass accretion, i.e., increase in mass and angular momentum and rejuvenation, favor chemical mixing by Eddington Sweet circulations in mass-accreting stars. Therefore, such a rapidly rotating star produced by

mass accretion should experience strong chemical mixing during the rest of its life, unless the orbit remains close enough for the star to be spun down by tidal interaction on a short time scale, after the mass transfer phase. If the secondary is rejuvenated sufficiently, even the quasi-chemically homogeneous evolution can be induced by mass accretion, eventually leading to production of a long GRB (Cantiello et al. 2007). This binary star scenario for long GRB progenitors suggests that a significant fraction of long GRBs should occur in runaway stars (see Fig. 6 and Cantiello et al. 2007) as implied by a recent observational study of Hammer et al (2006).

In short, a large fraction of massive binaries at very low metallicity may undergo dynamically stable Case C mass transfer. Therefore, most primaries in close binaries would explode as type Ibc supernovae, while most secondaries as type II supernovae, but some of them as long GRBs/hypernovae. The effects of chemical mixing such as production of primary nitrogen may be significant in mass accreting secondary stars.

#### 4. CONCLUDING REMARKS

We still do not fully understand the details about the effects of rotation such as transport processes of angular momentum and chemical species due to magnetic torques, Eddington Sweet circulations and other possible rotationally induced hydrodynamic instabilities in stars, which are important ingredients in recent stellar evolution models. Improved treatments of the rotation-related physics are thus needed for future studies, in connection with observational tests and multi-dimensional simulations (e.g. Brott et al. in this volume; Talon 2007). How-



**FIGURE 6.** Runaway star scenario for long GRB progenitors. In a close metal poor binary system, the secondary gains mass and angular momentum from the primary. If the secondary is rejuvenated and spun up sufficiently as a result, it undergoes the quasi-chemically homogeneous evolution. The primary becomes a WR star and explode as a type Ib/c supernova. If the supernova kick unbounds the system, the secondary runs away at a velocity of  $\sim 10\text{--}100$  km/s, and explode as a long GRB/hypernova after traveling a few to several hundreds PCs away. See Cantiello et al. (2007) for detailed discussions.

ever, above discussions clearly indicate that the evolution of metal poor massive stars much depends on rotation. Addressing the role of the massive star feed back in the early universe including the effects of rotation and binarity will be an exciting but challenging subject for the next decade. In particular, future observational studies on massive star populations (e.g. WR/O ratio) in metal poor galaxies and supernovae/GRBs at high redshift may provide strong constraints for theoretical models, as discussed in Yoon, Langer & Norman (2006) in greater detail.

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